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Abstract

These lectures survey the present situation and future prospects in selected areas of particle physics phenomenology: (1) the top quark, (2) the Higgs boson in the Standard Model, (3) strong WW scattering, (4) supersymmetry, (5) the Higgs sector in minimal supersymmetry, (6) low-energy constraints on supersymmetry.

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GENERAL INTRODUCTION

Our present understanding of elementary particle phenomena is dominated by the Standard Model (SM), based on three generations of basic spin-1/2 fermions (quarks and leptons), plus the spin-1 gauge fields of $\mathrm{SU(3)} \times \mathrm{SU(2)_L} \times \mathrm{U(1)}$ symmetry, plus spontaneous symmetry breaking by one doublet of spin-0 scalar fields. The SM works amazingly well — all of its predictions that can be tested have so far been verified to high precision; no discrepancies have yet been found. However the predicted top quark has not yet been confirmed experimentally, nor has the Higgs boson. The top quark is not seriously in doubt, since lots of indirect evidence points to its existence, but it is nevertheless important to discover it to determine its mass and other properties that enter many calculations. The symmetry-breaking sector appears to be much more arbitrary (one can easily imagine alternatives to the simple Higgs mechanism) and urgently requires investigation. This sector can be probed either by searching for the Higgs boson or by studying the scattering of longitudinally polarized W or Z bosons; these longitudinal states arise through symmetry-breaking and their scattering reflects the underlying mechanism. These topics are addressed in the first three lectures: (1) the top quark, (2) the standard model Higgs boson, (3) strong WW scattering.

The SM has severe shortcomings however. It contains many apparently arbitrary and unrelated parameters; this arbitrariness might be reduced or explained by some Grand Unified Theory (GUT), where the different gauge symmetries merge into a single higher symmetry and the masses may be simply related at a very high energy scale. But in plain GUT models associated with electroweak symmetry breaking an arbitrary fine-tuning of parameters seems to be needed to prevent the scalar particles from acquiring very large masses; a search for a solution to this "hierarchy problem" leads to Supersymmetry (SUSY), where every fermion has a boson partner and vice versa. No SUSY partners have yet been discovered but there is encouragement from the success of SUSY-GUT models, and indeed cosmological Dark Matter may be due to one of these particles. SUSY is also a likely ingredient in an eventual unification of strong and electroweak forces with gravity, while behind all this there lies perhaps a Superstring theory of everything. All sorts of new phenomena may arise beyond the SM: extra gauge bosons, exotic fermions, leptoquarks, nucleon decay, new classes of Yukawa interactions, etc. Some of these topics are addressed in the later lectures: (4) SUSY and GUTs, (5) Higgs sector in the minimum SUSY extension of the SM (MSSM), (6) low-energy constraints on SUSY.

We give a selection of references, but make no claim to completeness and specifically exclude references to standard textbook material.

LECTURE 1: THE TOP QUARK

1.1 Introduction

The top quark t is an essential part of the third fermion generation in the SM, together with the b-quark, the τ-lepton and its neutrino ν_τ. Their left and right chiral components have the usual $\mathrm{SU(2)_L} \times \mathrm{U(1)_Y}$ weak-isospin and hypercharge quantum numbers (with electric charge $Q = T_3 + \frac{1}{2}Y$):

	T_3	$\frac{1}{2}Y$
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\frac{1}{2}$ $-\frac{1}{2}$	$-\frac{1}{2}$ $-\frac{1}{2}$
τ_R	0	-1
$\begin{pmatrix} t \\ b \end{pmatrix}_L$	$\frac{1}{2}$ $-\frac{1}{2}$	$\frac{1}{6}$ $\frac{1}{6}$
t_R	0	$\frac{2}{3}$
b_R	0	$-\frac{1}{3}$

Here t (and ν_τ) are the only SM fermions to escape direct detection. In the case of t, this is apparently because it is very heavy [1],

$$m_t > 108 \text{ GeV} \qquad \text{(1993 SM CDF limit)} , \tag{1.1}$$

compared to other quarks ($m_u = 0.004,\ m_d = 0.007,\ m_s = 0.15,\ m_c = 1.3,\ m_b = 4.8$ GeV). But we have many indirect indications that top exists:

(a) It is needed to cancel chiral anomalies.

(b) It is needed for GIM-suppression of flavor-changing neutral currents. If b_L had no doublet partner t_L, then $BF(B \to \ell^+\ell^- X) > 0.013$ [2]; but the CLEO experimental bound is < 0.0012 at 90% CL [3]. Also, if b were an $\mathrm{SU}(2)_L$ singlet, B_d^0-$\bar{B}_d^0$ oscillations would be near maximal [4] but in fact they are not.

(c) The $e^+e^- \to \bar{b}b$ forward-backward asymmetry measures $T_3(b_L) - T_3(b_R)$; LEP data give a value $-0.504^{+0.018}_{-0.011}$ [5], confirming the SM value $-1/2$ and showing that b_L belongs to a doublet.

(d) With a singlet assignment for b, the predicted $Z \to b\bar{b}$ partial width is a factor of 15 times smaller than the measured value [4].

(e) Electroweak radiative corrections to all available Z, W and deep inelastic scattering data fit beautifully but require top-quark contributions with a mass of order [6]

$$m_t = 141 \begin{matrix} +17 \, +17 \\ -19 \, -18 \end{matrix} \text{ GeV} \qquad \text{(SM electroweak)} \; . \tag{1.2}$$

1.2 Top production, decay and detection

Top decays dominantly by $t \to bW^+$ in the SM (Fig. 1); other charged-current decays to dW or sW are suppressed by small KM matrix elements; neutral-current decays to uZ or cZ are suppressed by the GIM mechanism. Here W is now known to be on-shell [see Eq. (1.1)] and its subsequent decays are dominantly $W^+ \to u\bar{d}$, $c\bar{s}$, $\nu\bar{e}$, $\nu\bar{\mu}$, $\nu\bar{\tau}$ with respective branching fractions 1/3, 1/3, 1/9, 1/9, 1/9, approximately. The semileptonic modes $t \to be\nu$, $b\mu\nu$ provide the cleanest signatures, typically containing

(a) an energetic lepton, isolated from jets,

(b) missing energy and momentum,

(c) a b-jet, possibly tagged by a muon from $b \to c\mu\nu$ decay,

(d) a displaced vertex from b-decay (long lifetime),

which help to separate top events from backgrounds.

Fig. 1: Top decay in the SM.

If m_t is close to threshold, the mean lifetime $\tau = 1/\Gamma$ is long enough to allow the usual fragmentation (formation of a hadron) before the top quark decays. But if $m_t \gtrsim 120$ GeV the lifetime is too short to form any hadron (including toponium states) and top essentially decays as a free quark; in this regime its width is

$$\Gamma(t \to bW) \sim 0.17 (m_t/M_W)^3 \text{ GeV} \; , \tag{1.3}$$

shown in Fig. 2 [7]. Γ_t may be measured from the linewidth; there are also interference effects between gluons radiated from t and b, which depend sensitively on the top lifetime [8].

Fig. 2: SM top decay width versus m_t. From Ref. [7].

The only present machine that can now discover SM top quarks is the Fermilab Tevatron $p\bar{p}$ collider, with CM energy $\sqrt{s} = 1.8$ TeV. The lowest-order (α_s^2) QCD production subprocesses are light quark-antiquark and gluon-gluon fusion (Fig. 3).

Fig. 3: $t\bar{t}$ production via QCD at the Tevatron.

The total cross section is given by a convolution of subprocess cross sections $\hat{\sigma}$ with parton distributions of the general form

$$\sigma(s) = \sum_{i,j} \int dx_1 dx_2 \hat{\sigma}_{ij}(x_1 x_2 s,\, \mu^2) f_i^A(x_1,\, \mu) f_j^B(x_2,\, \mu)\ , \tag{1.4}$$

where A and B denote the incident hadrons, i and j are the initial partons, x_1 and x_2 are their longitudinal momentum fractions, and μ is the renormalization scale. The $t\bar{t}$ hadroproduction cross section has been calculated to the next order (α_s^3) [9]; there are uncertainties from the parton distributions and also from the choice of scale (Fig. 4). Electroweak subprocesses such as $W^+g \to t\bar{b}$, producing single top quarks, are also interesting but not competitive at the Tevatron[10].

Fig. 4: Range of predictions for $\sigma(p\bar{p} \to t\bar{t}X)$ at $\sqrt{s} = 1.8$ TeV at order α_s^3, with various scales μ. From Ref. [11].

To detect $t\bar{t}$ production is not easy: it is only a tiny fraction of the total cross section and fake events (containing leptons and jets) can arise from relatively copious production of b-quarks and W or Z. For $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV we have [12]

$\sigma(\text{total})$	$70\ \text{mb} = 7 \times 10^{-26}\,\text{cm}^2$
$\sigma(b\bar{b})$	$30\ \mu\text{b} = 3 \times 10^{-29}\,\text{cm}^2$
$\sigma(W)$	$20\ \text{nb} = 2 \times 10^{-32}\,\text{cm}^2$
$\sigma(Z)$	$2\ \text{nb} = 2 \times 10^{-33}\,\text{cm}^2$
$\sigma(t\bar{t})_{m_t=150}$	$10\ \text{pb} = 1 \times 10^{-35}\,\text{cm}^2$

The reliability of QCD calculations has been tested by b-quark data; Figure 5 shows that CDF measurements of inclusive b-production for transverse momentum $p_T(b) > p_T^{\min}$ approximately agree with expectations [12].

The number of observed events in a given channel is

$$N_{\text{events}} = \sigma \times \text{BF} \times \int \mathcal{L} dt \times \text{efficiency}\ . \tag{1.5}$$

Here $\int \mathcal{L} dt$ is the integrated luminosity, for which the CDF detector accumulated about 4 pb^{-1} up to 1989. However the D0 detector is now working too and the accelerator may deliver 25 pb^{-1} per detector in the 1992–3 running, rising to 75 pb^{-1} in 1994 and eventually (with a new main injector) up to 1000 pb^{-1} in 1997. A possible increase of energy to $\sqrt{s} = 2$ TeV in 1994 would increase the $t\bar{t}$ signal by about 30% for $m_t = 150$ GeV.

Fig. 5: Inclusive $p\bar{p} \to bX$ cross sections versus $p_T^{\min}$; preliminary CDF data are compared with QCD expectations. From Ref. [12].

Top events have the structure $p\bar{p} \to t\bar{t} \to (bW^+)(\bar{b}W^-)$ where typically the b-quarks appear as jets and each W-boson appears either as an isolated lepton (plus invisible neutrino) or as a pair of quark jets. However, the various partons can also radiate additional gluons or quarks, and final state partons can overlap, so the net number of jets is not fixed. Typical topologies for $t\bar{t}$ signal and $b\bar{b}$ background events are shown in Fig. 6. The $b\bar{b}$ background process produces a lepton in or near a jet (i.e. non-isolated) and can be greatly suppressed by a stringent isolation requirement. The other major background, from $W+$QCD jets, can give isolated leptons but usually gives less central jet activity than the $t\bar{t}$ signal; furthermore the jets usually do not contain a b-jet.

Fig. 6: Topologies of typical $t\bar{t}$ signal and $b\bar{b}$ background events.

1.3 Top search strategies

Exploiting the leptonic W-decays, one usually requires either one or two isolated leptons, for which $t\bar{t}$ states have the following branching fractions:

$$\begin{aligned} B(t\bar{t} \to e\mu X) &= 0.024\ , \\ B(t\bar{t} \to ee \text{ or } \mu\mu X) &= 0.024\ , \\ B(t\bar{t} \to e \text{ or } \mu + jets) &= 0.29\ . \end{aligned} \tag{1.6}$$

There are then various strategies, based on detecting

(a) Dileptons: this is the smallest but cleanest channel. We require two isolated opposite-sign leptons, not back-to-back, plus missing-p_T (denoted $\not{p}_T$). The $b\bar{b}$ background is suppressed (mostly non-isolated and back-to-back in azimuth); $W+$jets does not contribute; Drell-Yan and $Z+$jets is suppressed by $\not{p}_T$ (and additionally if we restrict to $e\mu$ cases). A small background from direct WW and WZ production remains, further suppressed by requiring extra jets.

(b) Single lepton plus jets: this is bigger but dirtier. We require one isolated lepton plus large $\not{p}_T$ plus several jets, of which two have invariant mass $m(jj) \sim M_W$. Then $b\bar{b}$ is suppressed but $W+$jets is only partly suppressed. This signal is bigger [see Eq. (1.6)] and also offers a complete reconstruction of top from 3 of the jets (unlike (a) where there is always a missing neutrino), but the $W+$jets background remains problematical.

(c) b-tags. The presence of a muon near a jet, with $p_T > 1$ GeV relative to the jet axis, tags it as probably a b-jet. Also the presence of a displaced vertex (with suitable conditions on the emerging tracks) can give an efficient b-tag. Adding such a tag would purify both signals (a) and (b) above, but at some cost to the signal event rate — perhaps a factor 10 for muon-tagging or a factor 3 for vertex-tagging. CDF have used muon-based b-tagging to sharpen up their top search in the single-isolated-lepton channel; a vertex-tagger is now in use too. A recent study of b-tagging in the heavy-top search is given in Ref. [13]

We can illustrate this discussion with some numbers, assuming integrated luminosity 100 pb^{-1}, acceptance cuts $p_T > 15$ GeV on each lepton and jet and $\not{p}_T$, plus further detection efficiency factors 50% for each lepton. Predicted numbers of events are then [14]

m_t (GeV)	σ (pb)	$e + \mu(+2\,\mathrm{jets})$	e or $\mu > 2\,\mathrm{jets}$
100	88	50 (30)	570
120	34	20 (16)	300
140	15	10 (9)	160
180	3	2 (2)	40
backgrounds			
$Z \to \tau\tau$	200	30 (7)	
$W \to \ell\nu$	4400		150

Comparing this with the current Tevatron situation (luminosity ≈ 20 pb^{-1}) we would expect about 4(2) $e\mu$ candidate events for $m_t = 120(140)$ GeV, in the range preferred by SM theory Eq. (1.2). In fact there are three candidate $t\bar{t} \to$ dilepton events from CDF and one from D0, so the numbers are not inconsistent with expectations for $m_t \lesssim 160$ GeV.

Figures 7–10 illustrate important aspects of the dilepton search strategy [15]. Figure 7 shows how a missing-p_T cut (in this case $\not{p}_T > 20$ GeV) discriminates strongly against $\gamma^* \to \ell^+\ell^-$ and $Z \to \ell^+\ell^-$ backgrounds. Figure 8 shows how an azimuthal angle-difference cut $30^\circ < \Delta\phi(\ell^+\ell^-) < 150^\circ$ discriminates against $b\bar{b} \to \ell^+\ell^-$ backgrounds. Figure 9 shows how the number of accompanying jets in $t\bar{t} \to \ell^+\ell^-$ events changes with m_t; we see that in the neighborhood $m_t \sim M_W + m_b$ the recoiling b-quarks are too soft to form jets so the multiplicity falls, and it is not efficient to demand jets here. Fortunately the $t\bar{t}$ signal here is much stronger than the remaining backgrounds and we do not need help. At higher m_t values where the signal falls and the WW background becomes a problem, the b-jets are hard and can be used for additional discrimination. Finally, Fig. 10 shows that the $t\bar{t} \to \ell^+\ell^-$ signal can be distinguished for higher masses $m_t = 150$–200 GeV and even beyond, by making a more severe requirement $p_T > 30$ GeV on the two accompanying jets; the b-jets from $t \to bW$ are naturally very hard in this mass range so there is little cost to the signal, but the $WWjj$ background goes down by a factor 4. The good news in all this is that the "gold-plated" dilepton signal remains essentially background-free through the whole of the SM-favored mass range and well beyond.

Fig. 7: γ^* and Z backgrounds to the top dilepton signal are suppressed by a cut $\not{p}_T > 20$ GeV [15].

Fig. 8: The $b\bar{b}$ background to the top dilepton signal is suppressed by rejecting back-to-back leptons (in azimuth), with a cut $30^\circ < \Delta\phi < 150^\circ$ [15].

Fig. 9: Topological cross sections for dileptons plus n jets, versus m_t, at the Tevatron (detection efficiency factor ~ 0.3 not included) [15].

Fig. 10: $p\bar{p} \to$ dilepton + 2-jet event rates at $\sqrt{s} = 2$ TeV, for $t\bar{t}$ signal and $WWjj$ background. Jet cuts $p_T(j) > 15$, 30 GeV are compared [15].

We turn now to single-lepton search strategies, seeking $t\bar{t}$ events with one $t \to bW \to b\ell\nu$ plus one $t \to bW \to bjj$ decay. We start simply by looking for $W \to \ell\nu$ events, requiring a hard isolated lepton plus substantial $\not{p}_T$; the distinctive signature of $W \to \ell\nu$ is that the "transverse mass" m_T peaks sharply near M_W. Here m_T is defined by

$$m_T^2(e\nu) = (p_{Te} + \not{p}_T)^2 - (\vec{p}_{Te} + \vec{\not{p}}_T)^2 = 2p_{Te}\not{p}_T(1 - \cos\phi_{e\nu}) \tag{1.7}$$

and its peak is a kinematical property, related to the "Jacobian" peaks of $p_T(e)$ and $p_T(\nu) \simeq \not{p}_T$, but with the special virtue that it is much less smeared by transverse motion of the W. For on-shell W-decays the shape of the m_T distribution is predictable. If $m_t < M_W + m_b$, $t\bar{t}$ events would contribute off-shell W-decays that would distort the shape in a characteristic way; Figs. 11 and 12 show theoretical examples and some real data. Since the $t\bar{t}$ signal has typically several accompanying jets while the background from plain W-production has typically little jet activity, the signal becomes more striking when we require more jets (Fig. 11); it should be detectable in events with $n \geq 2$ jets [15]. Figure 12 shows comparisons of theoretical distributions with CDF 2-jet and 1-jet data; the absence of any detectable signal in the early CDF data gave a limit $m_t > 77$ GeV at 95% CL.

If however $m_t > M_W + m_b$, the W is mostly on-shell and no distortion of the m_T distribution is expected. In this case we must simply look for an excess in $W + n$-jets events, compared to the background from plain W production. This background is huge. To reduce it we first require that n be large, say $n \geq 3$ or $n \geq 4$. We can also require that two of the jets have invariant mass $m(jj) \simeq M_W$ (since the signal contains $W \to jj$), but with experimental uncertainties and many possible jet pairings this condition is not very stringent. It is much more effective to require that one jet is b-tagged, as shown in Fig. 13; the cross sections shown here do NOT include the tagging efficiency, which depends on experimental details but is of

Fig. 11: Theoretical examples of single-lepton signals in the m_T distribution, for $m_t < M_W + m_b$; n denotes jet multiplicity [15].

Fig. 12: Single-lepton transverse mass distributions at the Tevatron with (a) 2 jets and (b) 1 jet. Solid curves are the calculated $W+$jets background, the dashed curve is the expected signal for $m_t = 70$ GeV [16].

order 30% for CDF vertex-tagging. We see that, after b-tagging and requiring $n \geq 3$, the $t\bar{t}$ signal greatly exceeds the $W +$ jets backgrounds through the range $m_t = 95$–170 GeV or so. The signal diminishes below 95 GeV because the b-jets get soft.

Fig. 13: Effects of b-tagging on the single-lepton $t\bar{t}$ signal at the Tevatron, for various jet multiplicities [14]. Jets and leptons are required to have $p_T(j) > 15$ GeV, $p_T(l) > 20$ GeV, $|\eta(j)| < 2$, $|\eta(l)| < 1$.

With an eventual luminosity 1000 pb^{-1}, the expected event yields at the Tevatron depend on m_t as follows [14]:

m_t (GeV)	e or $\mu + 4$ jets events	$e + \mu$ events
120	1380	240
140	850	98
180	260	24
210	140	12
240	60	5

The mass ranges where a firm signal could be established, and the lower bound that could be set in the case of no signal, depend on luminosity like this [14]:

$\mathcal{L}$	claim discovery	90% CL bound
$100\,\mathrm{pb}^{-1}$	$m_t \leq 150\,\mathrm{GeV}$	$> 180\,\mathrm{GeV}$
$1000\,\mathrm{pb}^{-1}$	$m_t \leq 220\,\mathrm{GeV}$	$> 250\,\mathrm{GeV}$

1.4 Further considerations

When a top signal is found, m_t can be estimated from various dynamical distributions that are sensitive to it [15], *e.g.*

(a) invariant masses $m(\ell_1, \ell_2)$ of two isolated leptons;

(b) invariant mass $m(\ell, \mu)$ of single isolated lepton and (opposite-sign) muon tagging the associated b-jet;

(c) invariant mass $m(jjj)$ of three jets accompanying single lepton;

(d) cluster transverse masses such as $m_T(\ell\ell jj, \not{p}_T)$;

(e) variables arising in families of explicit event reconstructions.

Maximum-likelihood methods can be used too [17,18]. With 1000 pb^{-1} of luminosity, the Tevatron could determine m_t to 5 GeV or better (at least up to about 170 GeV).

For the planned pp supercolliders SSC ($\sqrt{s} = 40$ TeV) near Dallas and LHC ($\sqrt{s} =$ 15.4 TeV originally, now 14 TeV) at CERN, $t\bar{t}$ production will be enormously larger than the Tevatron rates. Both the intrinsic cross sections (Fig. 14) and the planned luminosities are much bigger. If $m_t = 150$ GeV the cross sections and event rates will be

$$\begin{aligned} \text{SSC: } \sigma(pp \to t\bar{t}X) &= 12\,\mathrm{nb} \quad \text{giving } 1.2 \times 10^7 \text{ events/year}\ , \\ \text{LHC: } \sigma(pp \to t\bar{t}X) &= 2\,\mathrm{nb} \quad \text{giving } 2.0 \times 10^7 \text{ events/year}\ . \end{aligned}$$

One expects to measure m_t to 2–3 GeV using the distribution $m(\ell, \mu)$ of isolated lepton plus tagging muon described in (b) above; since both ℓ and μ originate from the same parent t, their invariant mass distribution (Fig. 15) depends only on the decay mechanism.

Fig. 14: $t\bar{t}$ production at the Tevatron, LHC and SSC [19].

Fig.15: m_t dependence of $m(\ell, \mu)$ distribution [20].

So far we have assumed purely $t \to bW$ SM decays, but other modes are possible beyond the SM. If there exist charged Higgs bosons $H^{\pm}$, then decays like

$$t \to bH^+ \to bc\bar{s},\, b\nu\bar{\tau}\ , \tag{1.8}$$

become possible. If the competing $t \to bH^+$ mode is strong it will reduce the SM $t \to bW$ branching fraction, reducing the SM signals we have discussed. In return we get some new signals: the $bc\bar{s}$ final state is similar to one of the SM modes but with a different mass peak at $m(c\bar{s}) = m_{H^+}$; the $b\nu\bar{\tau}$ mode can be recognized by an excess of τ over e or μ production (lepton non-universality). In models with two Higgs doublets the various branching fractions are controlled by a parameter $\tan\beta$, the ratio of the two vevs, constrained to lie in a range $0.2 \lesssim \tan\beta \lesssim 100$ if the couplings are perturbative [21]; Fig. 16 shows how the SM and Higgs modes compete and combine to give a range of possible $t \to be\nu$ and $t \to b\tau\nu$ fractions for an example with $m_t = 150$, $m_{H^+} = 100$ GeV. At large $\tan\beta$ a dramatic excess of τ over e or μ is predicted; but at small $\tan\beta$ both the SM signatures based on $t \to e(\mu)$ and the new signature based on $t \to \tau$ are strongly suppressed and top would be very difficult to discover at hadron colliders [22].

In SUSY models there may be other new modes such as

$$t \to \tilde{t}_1\tilde{Z}_i \to c\tilde{Z}_1\tilde{Z}_i\ , \tag{1.9}$$

where $\tilde{t}_1$ is the light squark partner of t, $\tilde{Z}_i$ are neutralinos (with $\tilde{Z}_1$ the lightest), if the SUSY particles are light enough. These too would compete and deplete the SM signals; a top quark as light as 65 GeV, with dominant SUSY decays, is not yet ruled out by Tevatron data [23].

Fig. 16: Sample $\tan\beta$ dependence of t and H^+ branching fractions[22]. The hidden top region where all semileptonic signals are suppressed is $\tan\beta \lesssim 0.3$.

Finally we come to the possibilities at future e^+e^- linear colliders, with luminosities of order 20 fb^{-1}/year. Figure 17 shows cross sections versus CM energy relative to the $e^+e^- \to \mu^+\mu^-$ cross section; the kink in the $e^+e^- \to \bar{q}q$ rate is due to $\bar{t}t$ production (here assuming $m_t = 150$ GeV). At $\sqrt{s} = 500$ GeV the $e^+e^- \to t\bar{t}$ event rate would be around 10^4/year, comparable with the Tevatron rather than the SSC; however the events would be much cleaner and top parameters would be easier to extract. An m_t measurement with statistical uncertainty 0.3 GeV from 10 fb^{-1} luminosity is expected [25]. The width Γ_t could also be accurately measured near the threshold energy, either from the energy-dependence of the cross section (Fig. 18), or from the momentum spectrum of t, or from a forward/backward asymmetry [7,25,26].

Fig. 17: Cross sections for possible high-energy e^+e^- colliders [24].

Fig. 18: $\sigma(e^+e^- \to \bar{t}t)$ near threshold [25].

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